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Environmental response of living benthic foraminifera in Kiel Fjord, SW Baltic Sea

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Abstract

The living benthic foraminiferal assemblages in the Kiel Fjord (SW Baltic Sea) were investigated in the years 2005 and 2006. The faunal studies were accomplished by geochemical analyses of surface sediments. In general, sediment pollution by copper, zinc, tin and lead was assessed as moderate in comparison with levels reported from other areas of the Baltic Sea. However, the inner Kiel fjord is still exposed to a high load of metals and organic matter due to enhanced accumulation of fine-grained sediments in conjunction with a concentration of pollution sources as shipyards, harbours and intensive traffic. The results of our survey showed that the dominant environmental forcing of benthic foraminifera is nutrients availability coupled with human impact. A comparison with data from the 1960s revealed apparent changes in species composition and population densities over the past decades. The stress-tolerant species *Ammonia beccarii* invaded Kiel Fjord whereas *Ammotium cassis* disappeared, possibly due to low salinity that prevailed 10 years ago. These changes in foraminiferal community and a significant increase of test abnormalities indicate enforced environmental stress since the 1960s.

1 Introduction

Benthic foraminifera of the Baltic Sea and Kiel Bight were investigated since the 19th century (Möbius, 1888). However, there is still lack of information concerning foraminiferal distribution in the Kiel Fjord. The available data are scattered, generalized or consider only the open Kiel Bight. Rumbler (1935) started systematically the ecological observations on foraminifera in the Kiel Bight. In the following, Rottgardt (1952) distinguished three different foraminiferal assemblages in the Baltic Sea: marine, brackish-marine (fjords and shallow areas of the Kiel Bight), and brackish faunas. But he investigated the total (living plus dead) assemblages as a systematic discernment between living and dead faunas by staining methods had not been established.

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A detailed taxonomical and ecological overview on benthic foraminifera in the Baltic Sea was provided by Lutze (1965), who also considered 5 stations in the Kiel Fjord. Wefer (1976) estimated the short-term dynamics of benthic foraminifera in the open Kiel Bight off Bokniseck. The benthic foraminiferal response to the 2004 spring bloom was investigated by Schoenfeld and Numberger (2007a) in the same area. The benthic foraminiferal distribution in the Kiel Fjord has been left out of sight. During the 20th century, this area has experienced a strong anthropogenic impact. In view of rising ecological problems, the environmental response of benthic foraminifera comes into focus of investigation.

A number of studies have addressed the foraminiferal reactions to environmental parameters as oxygen, salinity, temperature, food availability (e.g. Alve and Murray 1999; Gustafsson and Nordberg 2001) and contamination by trace metals (e.g. Yanko et al., 1998; Debenay et al., 2001). Surprisingly, no clear relationships between contaminant levels and foraminiferal community structures were recognized even in heavily polluted environments. In situ and in vitro experiments revealed, however, a decrease of foraminiferal population density, reproduction capability, enhanced mortality of some species, and increasing frequency of test abnormalities under the high trace metal or hydrocarbon concentrations (Alve and Olsgardt, 1999; Ernst et al., 2006; Le Cadre and Debenay, 2006).

Aim of this study was (1) to describe the distribution of living (stained) benthic foraminifera in the Kiel Fjord, (2) to investigate the distribution pattern of main geochemical parameters from surface sediments, (3) to outline the level of pollution by trace metals, and (4) to assess the foraminiferal response to environmental changes.

2 Study area

Kiel Fjord is a 9.5 km long, N-S extending and narrow inlet of south-western Kiel Bight (54°19'–54°30' N; 10° 06'–10°22' E). The Friedrichsort Sound divides the fjord into a southern, inner fjord with width to 250 m, and a northern outer fjord, which expands up

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to 7.5 km and passes into Kiel Bight (Fig. 1). The inner Kiel Fjord is mostly 10 to 12 m deep. A system of up to 16 m deep channels connects the inner with the outer fjord. The outer fjord itself is more than 20 m deep.

As the entire Kiel Fjord is relatively shallow and isolated, its hydrographic characteristics weakly depend on the salt-rich inflow water from the Belt Sea. The only river debouching into Kiel Fjord is the Schwentine.

The water masses of the inner fjord are homogeneously mixed, except during summer. Then, surface water has temperature up to 16°C and a salinity of about 14 units. The underlying deep water has a temperature of about 12°C and salinity of up to 21 units. In winter, the temperature – depth distribution is uniform and may be as low as to 2°C. The salinity is constant with depth as well (Schwarzer and Themann, 2003).

Pleistocene till is eroded at cliffs and on the shoals of Kiel Fjord. The coastal and near-shore erosion is the most important source of sediment in this area. The sediment transport is mainly directed from north to south into the fjord. Lag sediments with coarse sand and gravel prevail in the shallow coastal areas. They pass into sandy muds and silts in the deeper basins. In the innermost fjord, dark organic-rich muds are encountered even at shallow areas. Sand veneers are found in the Friedrichsort Sound due to relatively strong currents between inner and outer fjord (Schwarzer and Themann, 2003).

Kiel Fjord has seen an anthropogenic impact for the last 70th years by town infrastructure, shipyards, military and sport harbours and the intense traffic through Kiel Canal. The shipbuilding industry leads to substantial trace metal and oil pollution in places. Dredging to keep the seaways clear, and the ship traffic itself causes a strong redistribution and disturbance of surface sediments.

2.1 Previous pollution surveys

A number of studies on hydrography, sediment and organic matter distribution and pollution in the Kiel Bight have been carried during the 1960s–1970s by the former Special Research Unit (SFB) 95 of Kiel University. For the last decades, the environ-

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mental situation in Kiel Bight has been documented by annual reports of the Institute for Marine Research (IOW), Warnemünde. Some of these data are summoned in the Helsinki Commission proceedings. However, not many reports on the pollution of the Kiel Fjord itself are available despite the long-term anthropogenic load in this area. The recent investigation of trace metals pollution is performed and coordinated by the Regional Environmental Protection Agency (LANU) of the Bundesland Schleswig-Holstein (e.g. Haarich et al., 2003). Some measurements of metal concentrations have been made in Kiel Fjord in the frame of monitoring of the Kiel Bight by the IOW (e.g. Pohl et al., 2005). Oxygen distribution and eutrophication of the fjord was mentioned by Gerlach et al. (1984) and Schiewer and Gocke (1995). Rheinheimer (1998) and Kallmeyer (1997) outlined the history of pollution by organic compounds in fjord. Studies of trace metals in mollusks (ter Jung, 1992) and fish (Senocak, 1995) included Kiel Fjord as well. Recently, LANU investigated the distribution and effects of TBT on mollusks of Kiel Fjord (LANU, 2001).

3 Material and methods

3.1 Sampling

The current study is based on 61 surface sediment samples collected between December 2005 and May 2006 on 7 daily cruises with R/V *Polarfuchs*. The samples were retrieved with a Rumohr corer with a plastic tube of 56 mm inner diameter and a Van-Veen Grab. Latter was used when sandy sediments were encountered. Ruhmorcorer was deployed 3 times at each station in order to avoid errors associated with spatial patchiness. The uppermost centimetre of the sediment was removed on each deployment with a spoon. Surface sediments retrieved with the Van-Veen Grab were sampled with cut-off syringes, marked with centimeter-scale. The sediment was placed into a glass vial, thoroughly mixed and subsamples for organic and inorganic geochemical analyses were taken from this mixture at first. The remaining sample was transferred

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to a PVC vial, and preserved and stained with a solution of 2 g Rose Bengal per liter ethanol in order to mark foraminifers living at the time of sampling (Murray and Bowser, 2000).

3.2 Hydrographic measurements

- 5 The salinity, temperature and dissolved oxygen content of the superstanding water in the Rumohr corer tube was measured on board with Oxi- and Conductivity meters (Oxi323/325Set and LF320/Set). As these measurements were made within minutes after retrieval, and the air temperatures were not substantially higher than the water temperatures, we consider these values as representative for the near-bottom water.
- 10 In outer, middle and inner part of the Schwentine river, 3 CTD-profiles were done with WTW Profiline 197 TS in 1-m intervals to locate the boundary between riverine fresh water and higher- saline fjord waters.

3.3 Geochemical analysis

- 15 Subsamples for geochemical analysis were freeze-dried and powdered in an agate mortar. Measurements of C_{org} , total carbon (TC) and total nitrogen (TN) were performed with a Carlo Erba NA-1500-CNS analyzer at IFM-GEOMAR with accuracy better than $\pm 1.5\%$. Chlorophyll *a* and phaeopigments were determined after acetone extraction with a Turner TD-700 Fluorometer at IFM-GEOMAR. The precision of the method is $\pm 10\%$. Biogenic silica (opal) measurements were done according to an automated leaching method for the analysis of SiO_2 in sediments and particulate matter described by Müller and Schneider (1993) using a Skalar 6000 photometer with precision $\pm 1\%$. For trace metal analyses, the sediment samples were digested in a HNO_3 - HF - $HClO_4$ - HCl mixture solution. The solution was diluted and measurements were performed with an AGILENT 7500cs ICP-MS at the Institute of Geosciences, University of Kiel (Garbe-Schönberg, 1993). Blanks and the international standard MAG-1 were repeatedly analyzed together with the samples in order to evaluate the precision
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and accuracy of the measurements. The accuracy of analytical results as estimated from replicate standard measurements was better than $\pm 1.5\%$.

3.4 Foraminiferal studies

5 The sub-samples for foraminiferal analysis were stored in a fridge for two weeks to effect a sufficient staining with Rose Bengal. The samples were first passed through a 2000 μm screen in order to remove mollusks shells or big pebbles, and then gently washed through a 63- μm sieve. Sediments of the Baltic Sea have a high content of organic detritus. After drying, the detritus creates a film layer on the sample, which has to be disintegrated before picking (Lutze, 1965). In order to achieve a separation of
10 the organic detritus, the size fraction sieved through 63–2000 μm was transferred into the measuring cylinder with some tap water and left for a while. Then the supernatant water was decanted and poured through a filter paper to separate the major part of floating and suspended organic debris. During drying, the organic flocks stuck to the filter paper and foraminifera tests could be easily brushed off (Lehmann and Röttger,
15 1997). The 63–2000 μm and $>2000 \mu\text{m}$ fractions were dried at 60°C, weighed, and splitted. Well-stained foraminifers that were considered as living at the time of sampling were picked out from respective aliquots, sorted at species level, mounted in Plummer cell slides and counted. Both normal and abnormal tests were counted separately. The abundances were expressed as a number of specimens per 10 cm³ of sediment. The
20 main species were photographed by using a Scanning Electronic Microscope (Cam Scan) at the Institute of Geosciences, Kiel University.

4 Results and discussion

4.1 Hydrography

25 The temperature and salinity of near-bottom water in Kiel Fjord showed a pronounced seasonality. Temperature decreased from 8°C on average in December 2005 to

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2.3°8C in February, and raised again to 6.6°8C in May 2006. In December 2005, the near-bottom water showed the highest salinity with 23.2 units. The salinity decreased to a minimum in May when 16.5 units were measured.

In Schwentine river mouth, 3 CTD profiles were performed in February, and they revealed the boundary layer between riverine fresh water masses and saline water of the Kiel Fjord at approximately 1m depth. With a discharge of $7.3 \text{ m}^3 \text{ s}^{-1}$ on average the Schwentine substantially freshens the waters of the inner fjord.

The oxygen concentration exceeded $400 \mu\text{mol/l}$ and slightly decreased in the deep basins. The saturation levels varied from 58% to 100%. As such, a sincere oxygen deficiency in the near-bottom waters of Kiel Fjord was not recognized during the investigation period.

In addition, the oxygen saturation state was measured with a Unises microelectrode by Stefan Sommer, IFM-GEOMAR Kiel, in a short sediment core taken from the inner fjord. At 1 mm sediment depth, the saturation was still more than 50%, and a complete depletion of oxygen was encountered at 3.5 mm depth. As compared with a usual 2 to 5 cm thick oxic layer in normal marine settings, the oxygenated surface sediment layer in this core from Kiel Fjord was quite thin. But it apparently provided sufficient space and relatively good oxygen conditions for benthic foraminiferal populations.

4.2 Organic carbon and C/N ratio

The organic carbon content in the surface sediments ranged from 1 to 7.8%, and it is negatively correlated with the sand content ($R=-0.793$). The muddy sediments of Kiel Fjord contained up to 7.8% of C_{org} with a maximum in February to March, whereas the Friedrichsort Sound area is characterized by lowest C_{org} values of about 1% (Fig. 2). Apparently the seasonal increase of C_{org} in March is determined by the spring bloom, which usually falls in this period (e.g. Graf et al., 1982, Wasmund et al., 2005). Generally, the C_{org} content is higher than reported by Leipe et al. (1998) for Mecklenburg and Kiel Bights (5% for the fine fraction) and 3–5% in Flensburg Fjord (Exon, 1973). On the other hand, the sandy muds of Eckernförde Bight contain more

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than 13% C_{org} (Gerlach, 1990).

The mean C/N ratio depicted a substantial input of organic matter from the hinterland. The C/N ratio increased southwards from 4 in the outer fjord to 15 in the inner fjord. Perttilä et al. (2003) reported the same range of values for the southern Baltic Sea.

- 5 Seasonally, the C/N ratio changed not significantly but has the lower values in March and May that probably mirrors the accumulation of fresh detritus characterized by low C/N values of 5.6 to 7 (Graf et al., 1982).

4.3 Biogenic silica

- Biogenic silica (opal) content in surface sediments of Kiel Fjord was higher in spring as compared to December (0.1 wt.% to 8 wt.%), and showed a maximum in the inner fjord (Fig. 2). According to Wasmund et al. (2005, 2006) the spring blooms of 2004 and 2005 began in mid-March. The maximum of diatom biomass in bights of SW Baltic Sea was recorded in early April when also the biogenic silica flux to the sea floor showed peak values. Apparently, the increase of opal in sediments of Kiel fjord in February reflected an early spring bloom of diatoms in late February and March. Rathburn et al. (2001) and Bernardez et al. (2006) reported that surface sediment biogenic silica contents clearly reflects the spatial differences in surface water primary productivity. Rathburn et al. (2001) also suggested that at low depths and under relatively high sedimentation rates biogenic silica content in sediments could refer to seasonal changes of primary productivity. At the same time, Schwentine river might also be a source of opal for the inner fjord sediments because in the suspension of its water the opal values exceeded 15 wt.% due to freshwater diatoms. As the maximum of biogenic silica in inner fjord sediments was clearly apart from Schwentine mouth, we consider the primary productivity in the fjord as the main cause of seasonal and spatial variations in biogenic silica concentrations.

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4.4 Chlorine and phaeopigments

Chlorine concentrations in surface sediments varied from 7000 to 600 000 ng/g dry sediment (Fig. 2). In the observed period, we recorded an increase of chlorine content in the surface sediments from December to March. The spatial distribution of chlorine concentrations was irregular. In December and February, the highest concentrations were observed in the innermost fjord, while in March and May the chlorine levels were elevated towards the outer fjord. This pattern seems to depend on the development of the spring phytoplankton bloom; in particular the sequential grows of different algal groups and changes in hydrographical conditions (Graf et al., 1982) as well as terrigenous input.

The ratio of chlorophyll *a* and phaeopigments generally increased from February to May, which depicted flux of fresh, not degraded organic matter to the sea floor (Greiser and Faubel, 1988).

Apparently C_{org} , biogenic silica and chlorine content in sediments are significantly determined not only by the flux of phytodetritus to the sea floor but also by its accumulation in sediments, and they are therefore related to the sediment texture. Moreover, the distribution of phytoplankton pigments in the sediments is strongly governed by preservation conditions, oxygen regime, light and resuspension (Reussa et al., 2005). With the exception of resuspension, these parameters are considered to have a quite uniform distribution in Kiel Fjord.

4.5 Trace metals pollution

The concentrations of copper, zinc, tin and lead in surface sediments of Kiel Fjord show a high variability (Table 1). All heavy metal concentrations are positively correlated with the C_{org} contents and negatively correlated with the sediment proportion of $>63 \mu m$. The correlation infers that most of the trace metals are bound to organic matter, that they accumulate in muddy sediments, and that they are winnowed from of sandy sediment. In fact, elevated metal levels were recorded in the innermost and

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central fjord, where muddy sediments prevailed (Fig. 3). Moreover, exceptional high metal concentrations were found in surface sediments close to Lindenau shipyards at Friedrichsort, and at German Navy Tirpitzhafen. The sedimentation rate in Kiel Fjord is about 1 mm per year. With a given sample thickness of one centimeter, one has to keep in mind that our trace metal concentrations are an integral over last 10 years.

The long history of human impact in Kiel Fjord suggests that metal concentrations were substantially higher than the regional background determined for non-polluted coastal sediments in western Baltic Sea (HELCOM, 1993). Except in the innermost fjord, trace metal concentrations are well in the range of values reported from elsewhere in Kiel Bight during the years 1999 to 2004 however (Leipe et al., 1998; Haarich et al., 2003; Pohl et al., 2005).

Nonetheless, a trace metal study from a sediment core from Kiel Bight demonstrated that the metal concentrations systematically increased since the 1830s and reached maximum in 1950–1970s (Erlenkeuser et al., 1974). For instance, the youngest Cu, Zn and Pb contents were estimated as 70, 230 and 80 mg/kg respectively. Considering these values as background for the 1960s in Kiel Fjord, no significant changes in heavy metal concentrations took place during last 40 years. In some areas, we found even lower concentrations than in the 1960s, presumably due to environmental protection measures, banning of lead additives in gasoline, and the decline of shipyards activity in Kiel Fjord during the last decades. This scenario may also explain the relatively low concentrations of lead in Kiel Fjord while its main sources in the Baltic region are atmospheric input and surface runoff (Brüggmann, 1996). The tin concentrations were not reported in early investigations. In the southwestern Baltic Sea, tin contents of 2 to 2.5 mg/kg were found (Cato and Kjellin, 2005). The concentrations of tin measured in the 1970s in Flensburg Fjord also did not exceed 2.5 mg/kg (Untersuchungen..., 1973). With reference to these data, tin content in the inner part of Kiel Fjord has strongly elevated levels. This can be related to sport harbours and shipyards despite the recent restriction of tin-containing antifouling paints (IMO, 2001).

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4.6 Foraminiferal population density and species composition

The foraminiferal population density in Kiel Fjord ranged from 3 to 4895 ind./10cm³, on average 200 to 400 ind./10cm³. The living benthic foraminiferal communities were dominated by *Ammonia beccarii* (52% on average) and subspecies of *Elphidium excavatum* (together 44% on average). *Elphidium incertum*, *Elphidium albiumbilicatum* and *Elphidium gerthi* were common (5.3 and 3% on average). *Ammotium cassis*, *Reophax dentaliniformis regularis*, *Elphidium williamsoni*, and *Elphidium guntheri* were rare (maximal 2%). *A. beccarii* and *E. excavatum excavatum* presumably substitute each other in Kiel Fjord. *E. incertum* and *Elphidium albiumbilicatum* occurred together with moderate abundances in the area to both sides of Friedrichsort Sound. *Elphidium gerthi* and *Elphidium williamsoni* were recorded in shallow samples mainly near the shore (Fig. 4).

The arenaceous species *R. dentaliniformis regularis* and *A. cassis* were recorded only sporadically in our samples from Kiel Fjord. The situation was quite different in the 1960s, for instance Lutze (1965) reported *A. cassis* with 1 to 10% of the living fauna in 3 of his samples from Kiel Fjord (Fig. 5). We re-examined these samples curated at the Institute of Geosciences, Kiel University, and revisited Lutze's stations in February 2006 (Fig. 1b). Our samples revealed a foraminiferal population density that was about 100 times higher in 1963. We also did not find *A. cassis* here, but we observed *A. beccarii* with high abundances. *A. cassis* was common elsewhere in Kiel Bight until the mid 1990s (Schönfeld and Numberger, 2007a). Our results infer that this species has apparently disappeared in the 2000s from Kiel Fjord too, and that it has been presumably replaced by *A. beccarii*.

Positive correlations of population density with biogenic silica ($r=0.475$) and chlorophyll *a* ($r=0.600$) were found for samples taken in December. In March, the positive correlation of population density with opal and chlorophyll *a* was much better ($r=0.878$ and 0.834 correspondingly). This improvement underpins the strong relationship of the availability of food, in particular diatoms, and foraminiferal population density as it has

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been observed elsewhere in Kiel Bight (Altenbach, 1992; Schönfeld and Numberger, 2007b).

In order to reveal the stress response capability of the benthic foraminiferal fauna, we calculated the ration of the tolerant species *A. beccarii* vs. the specialized *E. excavatum* (A/E Index). The highest A/E values were found in the central part of Kiel Fjord. They coincide with high C_{org} levels (7%) and the highest tin load as observed in this study (18 mg/kg dry sediment).

E. albiumbilicatum abundances show a negative correlation with all trace metals. This foraminifer has been described as a typical shallow-water species (Lutze, 1965). Here, it inhabits the transitional area of Friedrichsort Sound where sandy sediments prevailed. The high water turbulences seemingly prevent the accumulation of organic matter bounded trace metals here. On the other hand, *E. albiumbilicatum* may have special capabilities to withstand the higher water turbulences in this sound, which the other foraminiferal species could not cope with and were swept away.

The outstanding increase in population densities as compared to previous studies in Kiel Fjord arises a question: why living foraminifera became so abundant since the 1960s, especially in presence of trace metals? According to Yanko et al. (1999), some foraminifera might respond positively when environmental insult is continuous. On the other hand, there are no data on trace metal concentrations in Kiel Fjord available from 1960s and therefore one cannot conclude that trace metals are the only factor that is responsible for the observed changes. Moreover, after the setup of sewage treatment plants and strict environmental protective politics in Germany and Scandinavian countries in 1990s (e.g. Danish Action Plan (I); HELCOM), which caused the decrease of industrial discharges and agricultural load, a general decrease of nutrient inputs and stabilization of oxygen levels in SW Baltic took place (Nausch et al., 2003, 2004). Despite the slight decline in nutrient levels since the mid 1990s, an increase of primary production by roughly 40% during the past 30 years has been reckoned for the western Baltic Sea (Wassmann, 1990; Schönfeld and Numberger, 2007). Provided this is applicable for Kiel Fjord too, even a doubling in primary production can not explain a

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29-fold increase in foraminiferal population densities from 29 ind/10cm³ on average in 1963 to 833 ind/10cm³ on average in 2005 and 2006.

4.7 Invasion and opportunistic behaviour of *Ammonia beccarii*

5 *A. beccarii* has ubiquitous distribution in the Kiel Fjord whereas both *E. excavatum* subspecies showed avoidance of central fjord with silty sediments enriched by C_{org} and tin. In the North Sea, Sharifi (1991) described *E. excavatum* as more frequent than *A. beccarii* in sediments polluted by Zn. According to Alve (1995), abundant and geographically widespread species are to be considered as most tolerant to environmental pollution. *A. beccarii* is commonly frequent in coastal and paralic environments
10 (e.g. Stouff et al. 1999). Taking all this into account, we consider that the main reason why *A. beccarii* is so abundant in Kiel Fjord, its opportunistic behavior and high potential to survive under high input of nutrients and trace metal concentrations.

4.8 Disappearance of *Ammonia cassis*

15 Sample PO220-37-2 taken in the Kiel Bight in 1996 had 90% of *A. cassis*, but did not contain any calcareous foraminifera. It well might be, that due to bad storage conditions, all the calcareous tests were dissolved in this sample. For this reason, we revisited station PO220-37-2 in December 2005 but we did not observe living *A. cassis* any more. Lutze (1965) stated that foraminifera in the Baltic Sea are mainly salinity and temperature dependant, and that *A. cassis* is adapted to a strong halocline between
20 surface and deep waters in Kiel Bight. Schönfeld and Numberger (2007a) suggested cyclic changes of *A. cassis* abundances depending on saltwater inbursts in the Kiel Bight and high salinity contrasts between surface and deep waters. According to our data, the inner Kiel Fjord is currently almost unpopulated by *A. cassis*. We observed only singular specimens in places. This pattern may be due to the fact that the inner
25 fjord is shallower, more closed and less saline than the open Kiel Bight. As such, the deep boundary layer, which is a necessary condition for successful reproduction of

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A. cassis as suggested by Olsson (1976), cannot establish in Kiel Fjord.

4.9 Test abnormalities

In the inner part of the Kiel fjord, we recorded high frequencies of test abnormalities (up to 18%). This is considerably higher than the typical value of 1% under natural undisturbed conditions (Yanko et al., 1999) (Fig. 4). The majority of abnormal tests were observed in *A. beccarii*. A high number of test abnormalities preferentially occurred in the inner fjord, where the highest trace metal levels prevailed. An exceptionally high abundance of abnormal tests (up to 20% of the living *Ammonia* population) were observed in sandy sediments of north-eastern part of the fjord, in the vicinity of Laboe resort, far from evident and dedicated pollution sources. During springtime, the frequencies of abnormal tests were positively correlated with Cu, Zn, Sn and Pb ($r=0.954$; 0.996 ; 0.914 ; 0.780 respectively). At the same time, the most of very tiny specimens recorded in Kiel Fjord also belong to *A. beccarii*. Experimental observation reported by Le Cadre and Debenay (2006) showed for *A. beccarii* that an increase in copper contamination may lead to a delay in growth and reproduction, which is then reflected in more frequent dwarfism and occurrence of new chamber deformations.

5 Conclusions

The results of the present study showed that labile organic compounds (biogenic opal, chlorines, C_{org}) in sediments of the Kiel Fjord were subjected to a strong seasonal variability. Their concentration was significantly higher in springtime. The spatial distribution of labile organic compounds is mainly determined by sediment type. Generally, the levels of concentrations of biogenic compounds are comparable to those reported from the open Kiel Bight. Markedly low levels of nutrients in Friedrichsort Sound establish quite unfavorable conditions for many benthic foraminiferal species. The surface sediment pollution by copper, zinc, tin and lead principally could be considered as mod-

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erate because the levels of metals are comparable to ones elsewhere in the Baltic Sea. Nevertheless the inner Kiel fjord is distinguished by a high load of heavy metals. The high tin concentrations in surface sediments apparently depend on its accumulation in muddy sediments for previous decades.

5 Analysis of foraminiferal population density showed a patchy distribution and a response to food availability, which is depicted by SiO₂ and Chl *a* in the sediments. The strong increase of population density since the 1960s remains enigmatic. It cannot be scaled to the increase in organic matter supply and a slight reduction of pollution. Furthermore, we observed significant changes in foraminiferal species composition in
10 2005–2006 as compared to the 1960s. The highly stress tolerant species *A. beccarii* invaded Kiel Fjord. We suppose that this species is highly opportunistic and capable to tolerate elevated levels of nutrients and trace metals. *E. albiumbilicatum* apparently is able to withstand the higher water turbulences and therefore inhabits the transitional area of Friedrichsort Sound. Unfavorable salinity conditions in the Kiel Bight and ab-
15 sence of a deep halocline in Kiel Fjord might have caused the diminution of *A. cassis*. During the winter season, linkages between test abnormalities and trace metal concentrations were not obvious. However, during springtime we observed an increase in abundance of abnormal tests, which was correlated to high trace metal levels. We suggest that this mirrors the reproduction of benthic foraminifera during spring bloom, and that the juveniles were especially sensitive to environmental stress. The perian-
20 nual dominance of *Ammonia beccarii* is not affected by the increased abundance of malformations in juvenile specimens.

Faunal list

Taxonomic references were given by Lutze (1965) and are not included in the reference
25 list.

Ammonia beccarii (Linné) = *Nautilus beccarii* Linné, 1758

Ammotium cassis (Parker) = *Lituola cassis* Parker, 1870

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Elphidium albiumbilicatum (Weiss) = *Nonion pauciloculum* Cushman subsp. *albiumbilicatum* Weiss, 1954 (Note: *Elphidium asklundi* Brotzen, 1943 of Lutze (1965)).
Elphidium excavatum f. *excavatum* (Terquem) = *Polistomella excavata* Terquem, 1875, (Note: *Elphidium excavatum* f. *selseyensis* of authors)

5 *Elphidium excavatum* f. *clavatum* (Cushman), 1930

Elphidium gerthi van Voorthuysen, 1957

Elphidium guntheri Cole, 1931

Elphidium incertum (Williamson) = *Polystomella umbilicatula* (Walker) var. *incerta* Williamson, 1858.

10 *Elphidium williamsoni* Haynes, 1973 (Note: *Cribronionion* cf. *alvarezianum* Orbigny, 1839 of Lutze (1965))

Reophax dentainiformis f. *regularis* Höglund, 1947.

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Table 1. Mean (range) concentrations of trace metals (Cu, Zn, Sn, Pb) in the surface sediments of Kiel Fjord and their correlation with organic carbon content and sand ($>63\mu\text{m}$) percentage, number of samples $n=53$.

Trace metals, mg/kg	Kiel Fjord, mean (range)	Correlation coefficient (r) with C_{org} , %	Correlation coefficient (r) with sand content ($>63\mu\text{m}$), %
Cu	62.3 (1.79–162)	0.726	−0.581
Zn	185 (11.2–434)	0.770	−0.621
Sn	4.97 (0.24–18.4)	0.549	−0.404
Pb	118 (6.81–260)	0.675 ($n=52$)	−0.579 ($n=52$)

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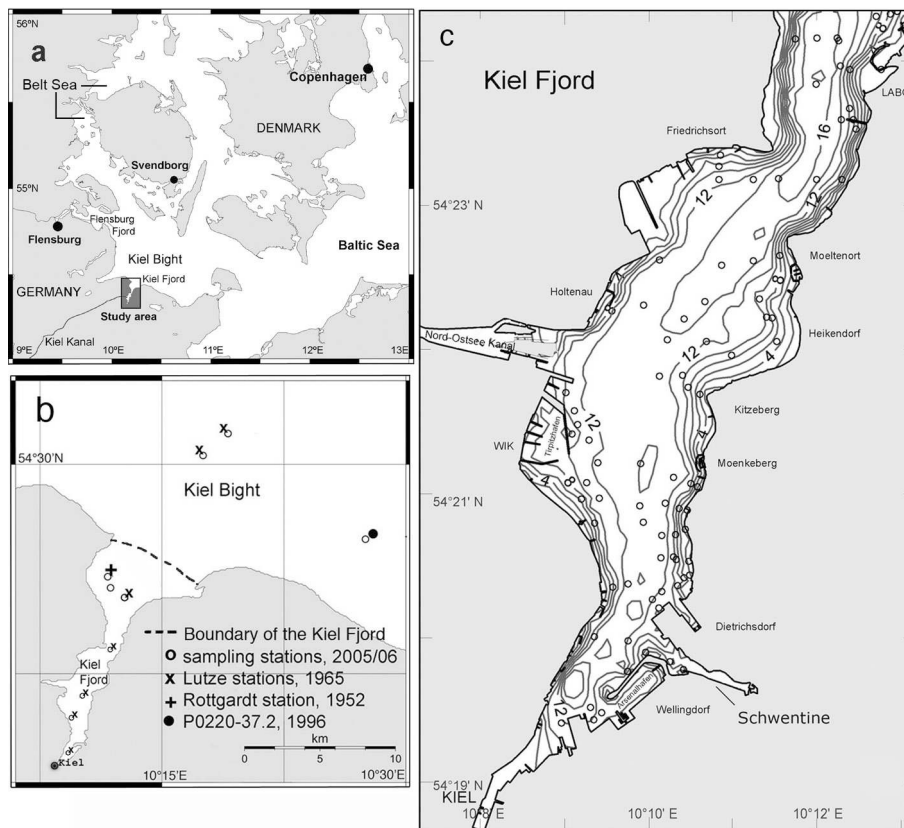


Fig. 1. Study area: **(a)** – SW Baltic Sea, **(b)** – outer Kiel fjord, **(c)** – inner Kiel Fjord with sampling stations.

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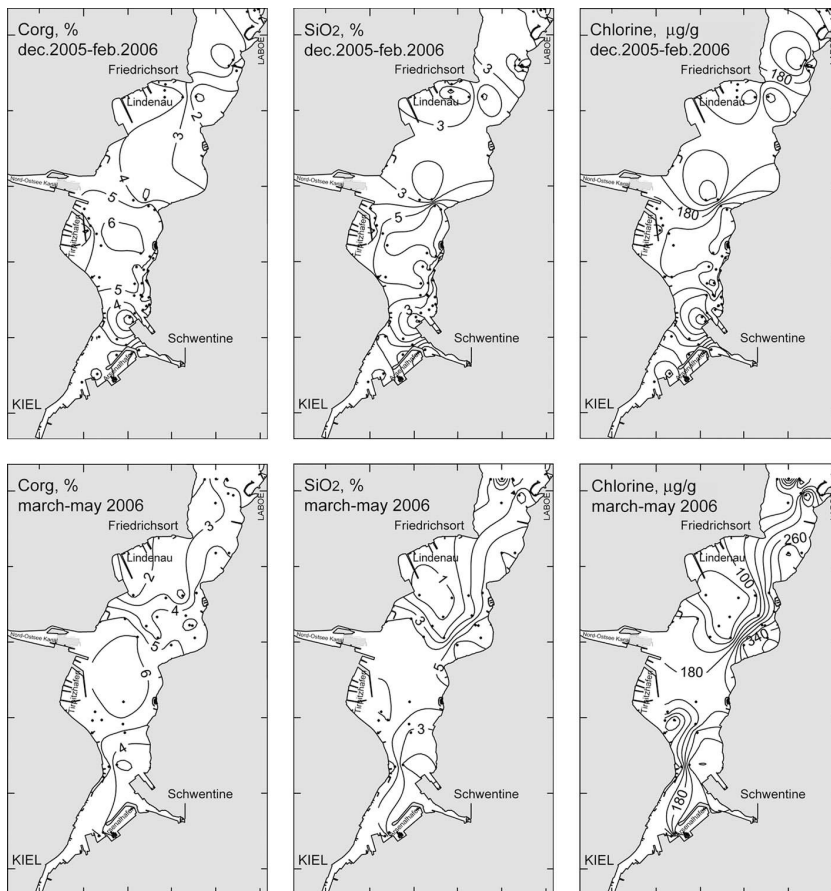


Fig. 2. Seasonal distribution of organic carbon (%), biogenic silica (wt.%) and chlorine (note: $\mu\text{g/g}$ instead of ng/g by other authors) in Kiel Fjord.

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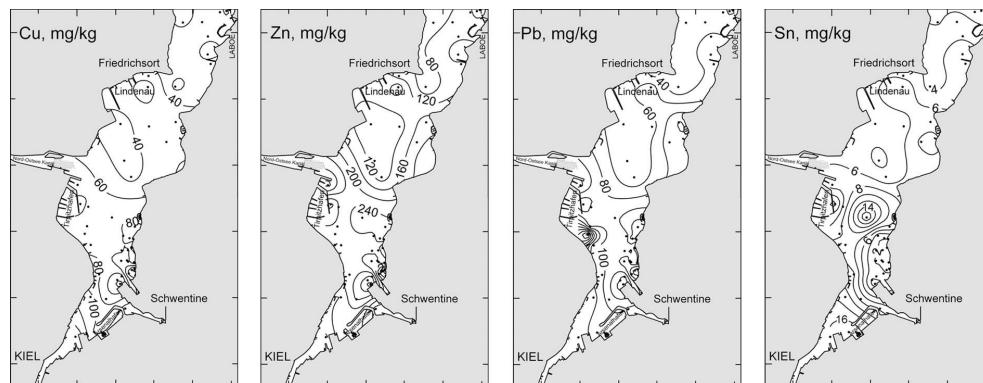


Fig. 3. Trace metals (Cu, Zn, Pb, Sn) distribution in the inner Kiel Fjord.

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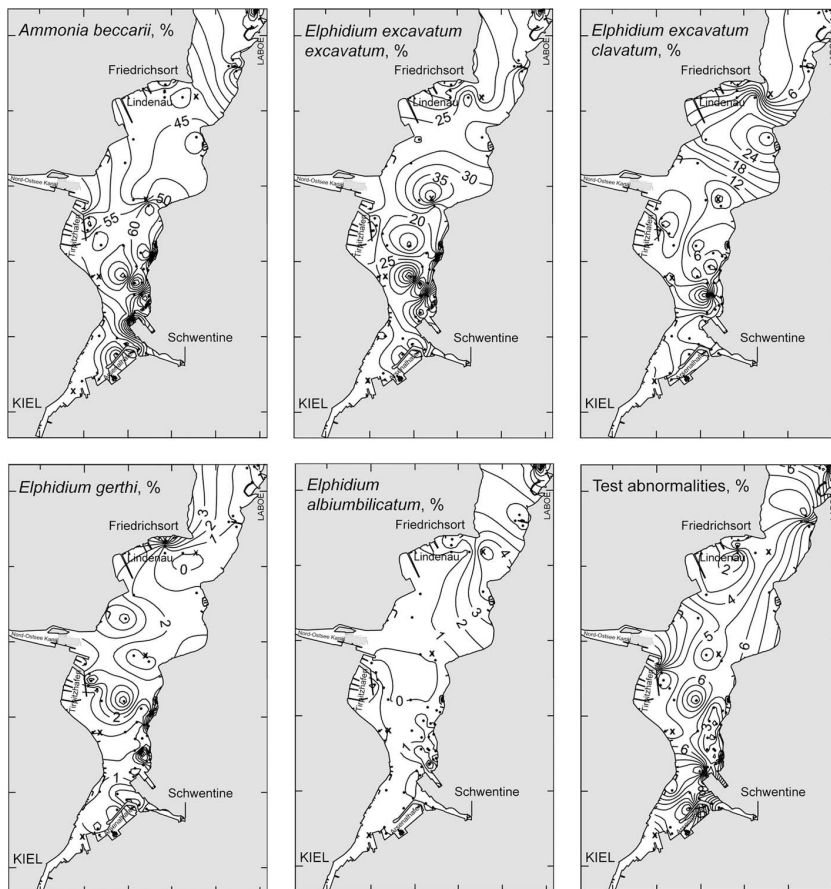


Fig. 4. Foraminiferal relative abundances and test abnormalities percentage in Kiel Fjord, here X indicates the stations revisited after Lutze (1965).

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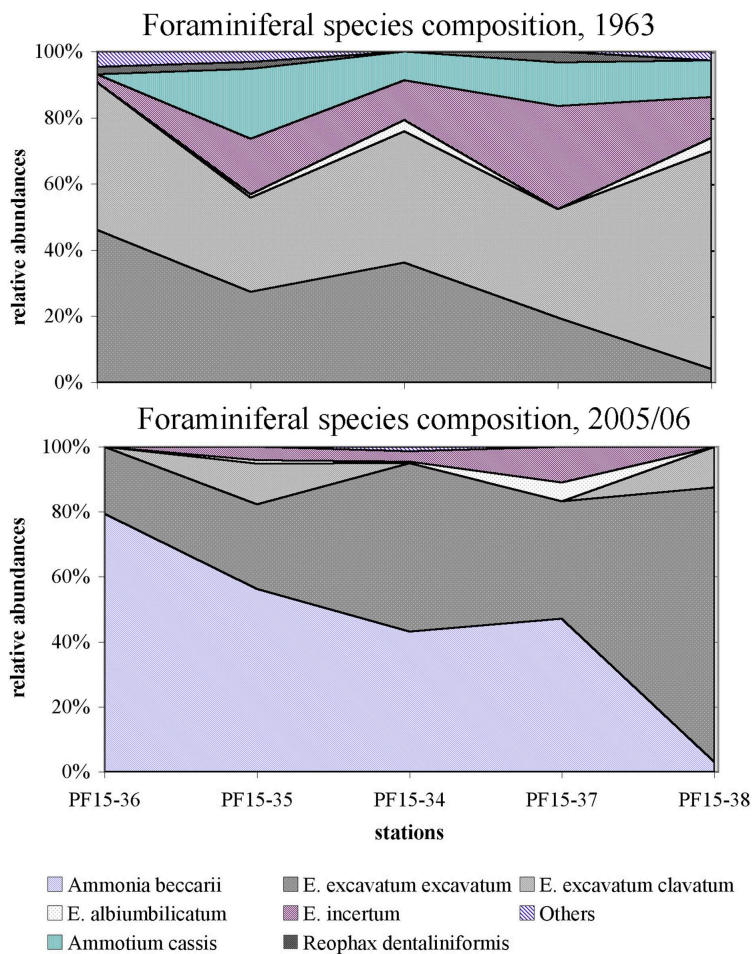


Fig. 5. Benthic foraminiferal species composition in 1963 (Lutze, 1965) and 2005/2006 along the Kiel Fjord from south to north.

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